7th ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2015
A.L. Araújo, C.A. Mota Soares, et al. (Editors)

CHARACTERIZATION OF SMART FLUID DAMPERS USING RESTORING FORCE SURFACE METHOD BASED ON ACCELERATION FEEDBACK

H. Metered[1], M. Kozek[2], Z. Šika[3]

[1]Czech Technical University in Prague, Prague, Czech Republic
[1]Vienna Technical University, Vienna, Austria
[1]Helwan University, Cairo, Egypt
Hassan.metered@yahoo.com

[2]Vienna Technical University
Vienna, Austria
martin.kozek@tuwien.ac.at

[3]Czech Technical University in Prague,
Prague, Czech Republic
Zbynek.Sika@fs.cvut.cz

Key words: Characterization, Smart fluid dampers, MR dampers, Restoring force surface, Acceleration feedback.

Summary: *The restoring force surface (RFS) method of nonlinear system characterization requires the simultaneous input of displacement, velocity and acceleration signals. A practical technique requires that only one of these quantities can be measured and estimate the others by numerical integration and/or differentiation. Up to now, the prediction of the damper force using RFS has been done before based on displacement and velocity measurements but these two input signals require expensive hardware equipment. The magnetorheological (MR) damper is one of the most famous smart fluid industrial applications because it has many advantages such as mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness.*

This paper introduces a precise selection of data input to the restoring force surface to predict the damping force of MR dampers. An RFS method for predicting the MR damper force based on acceleration feedback is investigated due to the advantages of the accelerometers. It consists of a two dimensional interpolation using Chebyshev orthogonal polynomial functions to identify the damping force as a function of the velocity, acceleration and input voltage. The identification and its validation are done based on simulated data generated by a theoretical model of an MR damper. Validation data sets representing a wide range of operating conditions of the MR damper show that the usage of RFS to predict the damping force for known velocity and acceleration is reasonably accurate compared to the prediction based on displacement and velocity.

1 INTRODUCTION

Controllable smart fluid dampers generally utilize either electrorheological (ER) fluids or magnetorheological (MR) fluids, whose viscosity properties can be altered dramatically by applying an electric field (ER) or a magnetic field (MR). This paper is focused on MR fluid dampers which are considered more suitable than ER fluid dampers for vibration applications. Due to the complex behavior of MR dampers under different operating conditions, their suitable models have been recognized as an interested research topic for the last two decades; a lot of previous published work of the literature on this topic can be found in [1], and the references therein. Basically, the introduced models can be classified into three categories: physical, rheological, and nonparametric models, each of them have some particular advantages and disadvantages.

Physical models [2, 3] depend on the detailed structure and the theory of operation of the MR damper. They define the dynamic behavior in different operating conditions very well. They are the most acceptable models from the theoretical point of view, but they have some drawbacks. First, they regularly are computationally complex, which needs more time for subroutines if they are implemented into a program, for example full vehicle model simulation. Second, they contain numerous parameters whose values can only be defined by expensive measurements with special testing devices, and even a small change in the MR damper design may need an adjustment of the model and a set of new measurements. Moreover, for most car producers it is vital to have the possibility of characterizing the parameters by their own using standard test devices. Truly, physical models of MR dampers for this purpose were introduced quite recently; however, the determination of certain parameter values by optimization techniques needs a lot of computational effort [4, 5].

Rheological models [6, 7] are combined of springs, dashpots, friction and backlash elements, and display similar advantages and disadvantages as physical models. For their good estimation of the MR damper behavior in a wide range of operating conditions, one pays the price of regularly time consuming subroutines and of tedious identification of the parameter values.

Nonparametric models [1 and the references therein] formulate a relation between measured or estimated variables, generally the force in one side and for example the displacement and the velocity in the other side, the identified parameters do not have any direct or physical meaning [8-11]. By comparison to the other types of models, they generally predict the dynamic behavior of the MR damper only in a limited range of operating conditions precisely, but as important advantage one achieves very time efficient subroutines, and the values of the parameters can be modified to a new set of test data easily.

This paper contributes a new way for constructing the RFS using the acceleration feedback to predict the MR damper force as a function of velocity, acceleration and input voltage using the two dimensional Chebyshev orthogonal polynomials fits. Also, a theoretical comparison between the four possible ways in weaving the force surface is done and the four surfaces are assessed. This functional representation could then be used to predict the damping force for different operating conditions, under any desired combination of voltage, amplitude, and frequency of the excitation signals, within the limits of the interpolation. The identification and its validation are done using a simulated data generated by the recent model of MR damper published in [5].

2 TARGET MODEL OF MR DAMPER

There are four steps to formulate a non-parametric MR damper model which can be summarized as follows:

The first step is to collect the identification data for the damper force under various inputs, i.e, the damping force owing to the sinusoidal input displacement of various amplitudes and frequencies, under possible working conditions, such as a constant applied voltage to the damper coil. The second step is to choose a proper identification technique to characterize the hysteretic loop between the sampled damper force and input signals. The third step is to identify the unknown coefficients of the proposed model using any method mentioned in the introduction. Finally, the proposed model has to be validated against the target model behavior in order to quantify its ability to track the target force. In this paper, the identification and validation are done using simulated data generated from the MR damper model published in ref. [5]. Equation (1) represents the damper force as a function of velocity $\dot{x}$, acceleration $\ddot{x}$ and input voltage to formulate the identification surfaces.

$$F_d = \left(f_0 + C_b \dot{x} + \frac{2}{\pi} f_{yl} \tan^{-1}\left[k\left(\dot{x} - \dot{x}_0 \operatorname{sgn} \ddot{x}\right)\right]\right)(w_1 a + w_2)(w_3 f + w_4) \qquad (1)$$

where,

$$f_{yl} = \frac{f_y}{1 + e^{-1.1(V-2.3)}}, \quad \dot{x}_0 = \frac{c_w}{1 + 1.81 e^{-0.2V}}, \quad C_b = \frac{c_b}{1 + \alpha e^{-\beta V}}$$

and f_0 is the offset force of the MR damper, c_b is the slope coefficient of the hysteresis curve, f_y and k are two coefficients characterizing the maximal damping force, and c_w is the width coefficient of the hysteresis curve, w_1 to w_4 are coefficients to generalize the model for any combinations of amplitude and frequency of the input signals, and F_d represents the restoring force of the MR damper. Table 1 shows the model parameters of the target model as listed in [5].

Table 1: Target model parameters of MR damper [5].

SYMBOL	VALUES
c_b	1.7
f_y	698.3
k	0.08
c_w	30
α	4.55
β	-2

3 RESTORING FORCE SURFACE USING CHEBYSHEV POLYNOMIALS FITS

This section introduces a brief description of the Chebyshev polynomial method to predict the damping force as a function of two variables. The damping force can be approximated as two dimensional interpolation fits involving two variables (v_1, v_2) either x, and $\dot{x}$ in the *displacement-velocity* model or $\dot{x}$ and $\ddot{x}$ in the *velocity-acceleration* model.

$$F(v_1,v_2) \approx \hat{F}(v_1,v_2) = \sum_{k,l=0}^{K,L} C_{kl} T_k(\tilde{v}_1) T_l(\tilde{v}_2) \tag{2}$$

where $\hat{F}(v_1,v_2)$ is the restoring force of the MR damper, C_{kl} are the normalized Chebyshev coefficients, T_k and T_l constitute the polynomial basis over which the force is projected and K and L are the polynomials' truncation orders. The coefficients C_{kl} can be determined by invoking the orthogonality properties of the chosen polynomials. The use of the Chebyshev polynomials makes the integrals required to evaluate these coefficients quite straightforward. The complete derivation of the coefficients C_{kl} was introduced before in details in ref. [8] for a three dimensional interpolation fit problem.

$$C_{kl} = \frac{4}{(1+\delta_{k0})(1+\delta_{l0})Q_\eta Q_\omega} * \sum_{i=1}^{Q_\eta} \sum_{j=1}^{Q\omega} \hat{F}(\eta_i,\omega_j) * \cos\left(\frac{2i-1}{2Q_\eta} k\pi\right) * \cos\left(\frac{2j-1}{2Q_\omega} l\pi\right) \tag{3}$$

where, δ_{ik} is the Kronecker delta and Q_η is the number of quadrature points. The determination of the coefficients C_{kl} from the above expression requires the values of the damper force at the grid points i.e. $\hat{F}(\eta_i,\omega_j)$. These are found as follows. For a particular voltage value, a surface can be constructed showing the force as a function of displacement and velocity or velocity and acceleration. Using the 2D-interpolation function *griddata* available in MATLAB, the $Q_\eta \times Q_\omega$ grid forces on a particular voltage surface can be determined i.e. $\hat{F}(\eta_i,\omega_j)$, $i = 1,2,....,Q_\eta$, $j = 1,2,....,Q_\omega$. Once the C_{kl} are determined, the predicted MR damper force can be predicted using the following relationships [13]:

$$T_0(x) = 1 , \quad T_1(x) = x , \quad T_2(x) = 2x^2 - 1$$

or

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x) \tag{4}$$

4 RESULTS AND DISCUSSION

The identification procedure of the MR damping force based on the two restoring force surface models, *displacement-velocity and velocity-acceleration*, is introduced in this section. Also, the predicted damping force from the polynomial model is compared against the damping force of the target model under different operating conditions.

4.1 Identification from displacement-velocity surface

A two-dimensional interpolation of the damper force as a function of displacement and velocity for a fixed voltage of 1.5V is achieved. This section introduces two different ways to generate the above described constant voltage surfaces:

(i) by "weaving" the surface from the results obtained from a series of tests conducted with prescribed sinusoidal displacement signals, all at the same frequency but of different amplitudes, according to the following input $A \sin(2f\pi t)$, A = [0.2:0.2:20] (mm) and f = 2 Hz. Figure (1) shows the generated surface plot produced by the target MR damper model according to this way, the forces at the grid points being indicated by red circles. These are used to calculate the 20×20 coefficients.

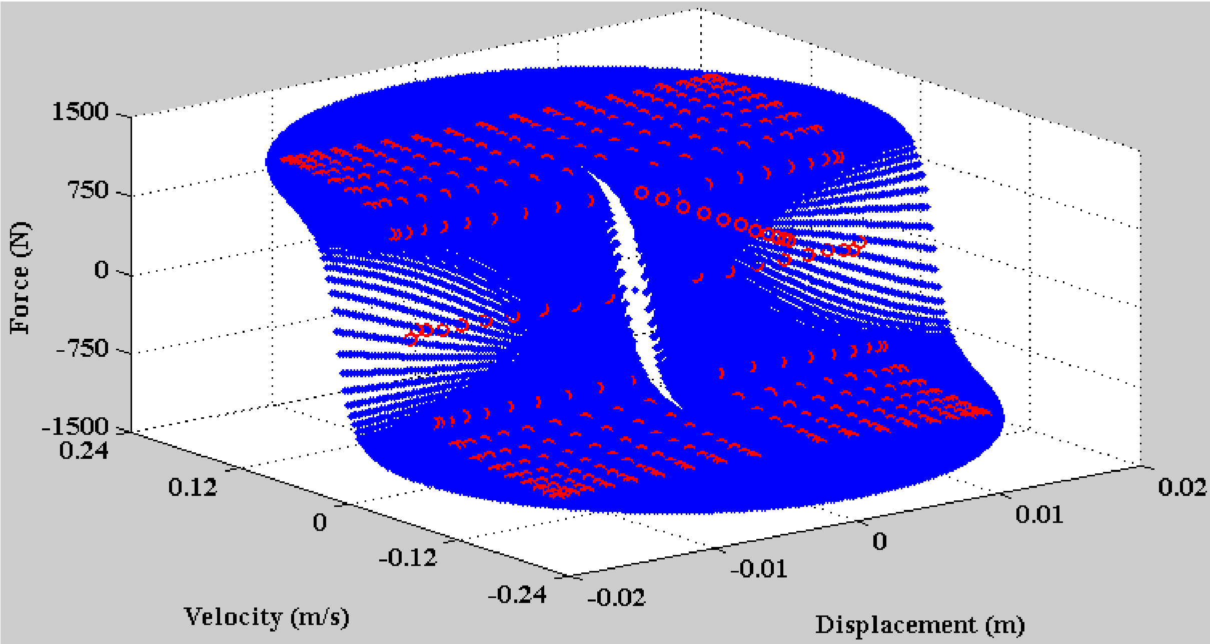

Figure 1: Surface plot of damping force generated by the target model according to different amplitudes.

(ii) by "weaving" the surface from the results obtained from a series of tests conducted with prescribed sinusoidal displacement signals, all at the same amplitude but at different frequencies, according to the following input $A \sin(2f\pi t)$, f = [0.02:0.02:2] (Hz) and A = 20 mm. Also, Figure (2) shows the generated surface plot produced by the target MR damper model according to this way, the forces at the grid points being indicated by red circles. These are used to calculate the 20×20 coefficients.

Table (2) lists a wide range of operating conditions of the MR damper and represents several sets of model validation. Two validation sets are introduced in this paper to quantify the success of the proposed technique. The sine wave is chosen to be the damper input with different amplitudes and frequencies. The first validation set has 16 mm amplitude, 2 Hz frequency and 2 V as the command voltage whereas the second one has 12 mm amplitude, 3 Hz frequency and 0.5 V as the command voltage.

Figures (3-6) demonstrate a good agreement between the predicted and target damper forces in general according to different validation sets, thus indicating that the proposed technique is able to predict the hysteresis force of the MR fluid damper.

Table 2: Validation data sets

SYMBOL	VALUE
Amplitude (mm)	[4 8 12 16 20]
Frequency (Hz)	[1 2 3]
Voltage (V)	[0.5 1 1.5 2 2.5 3]

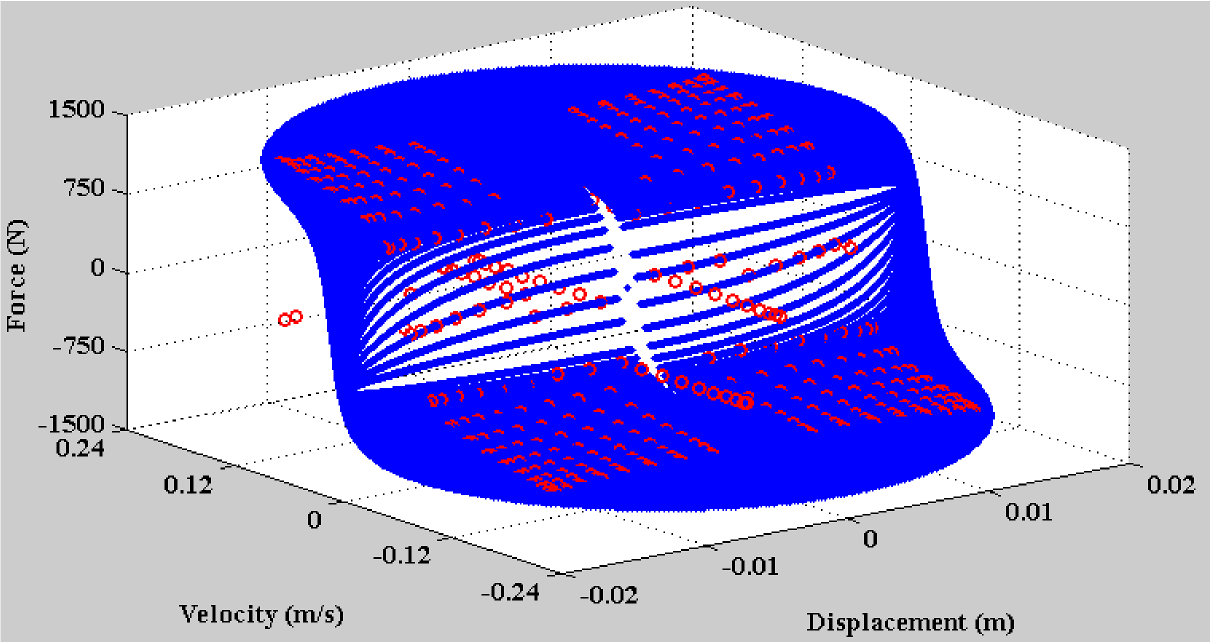

Figure 2: Surface plot of damping force generated by the target model according to different frequencies.

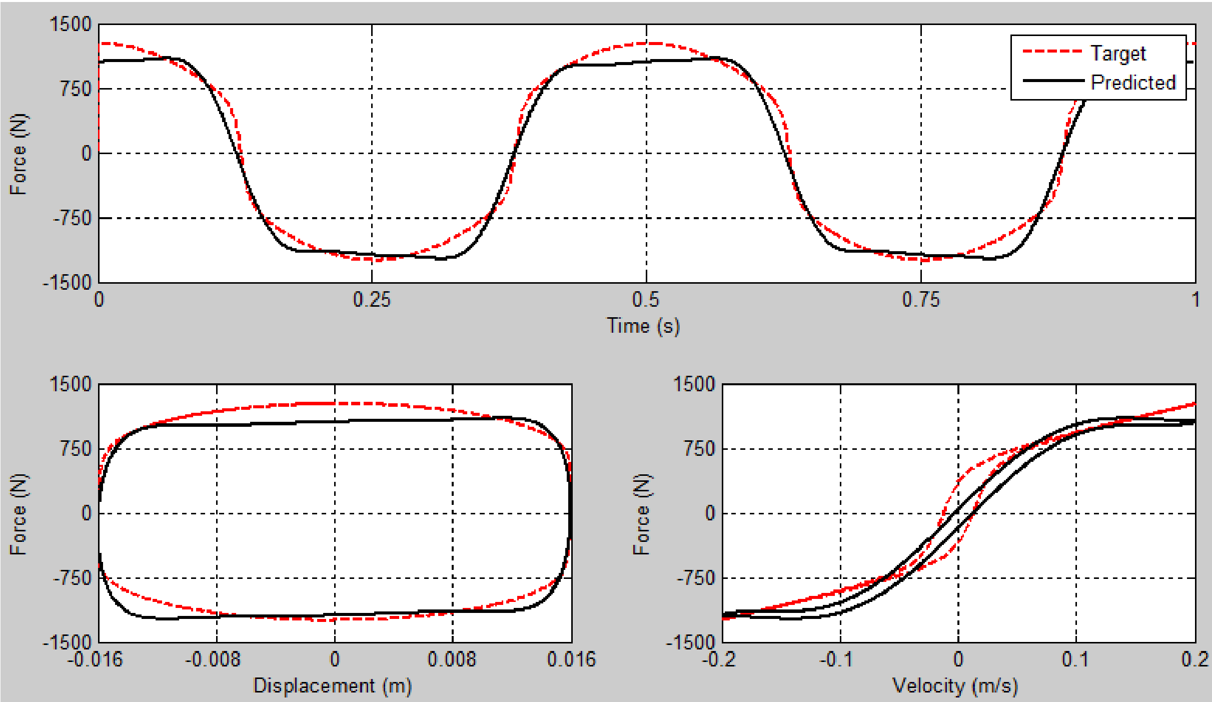

Figure 3: Validation of interpolation procedure derived from surface plot in figure (1) according to the validation set 1.

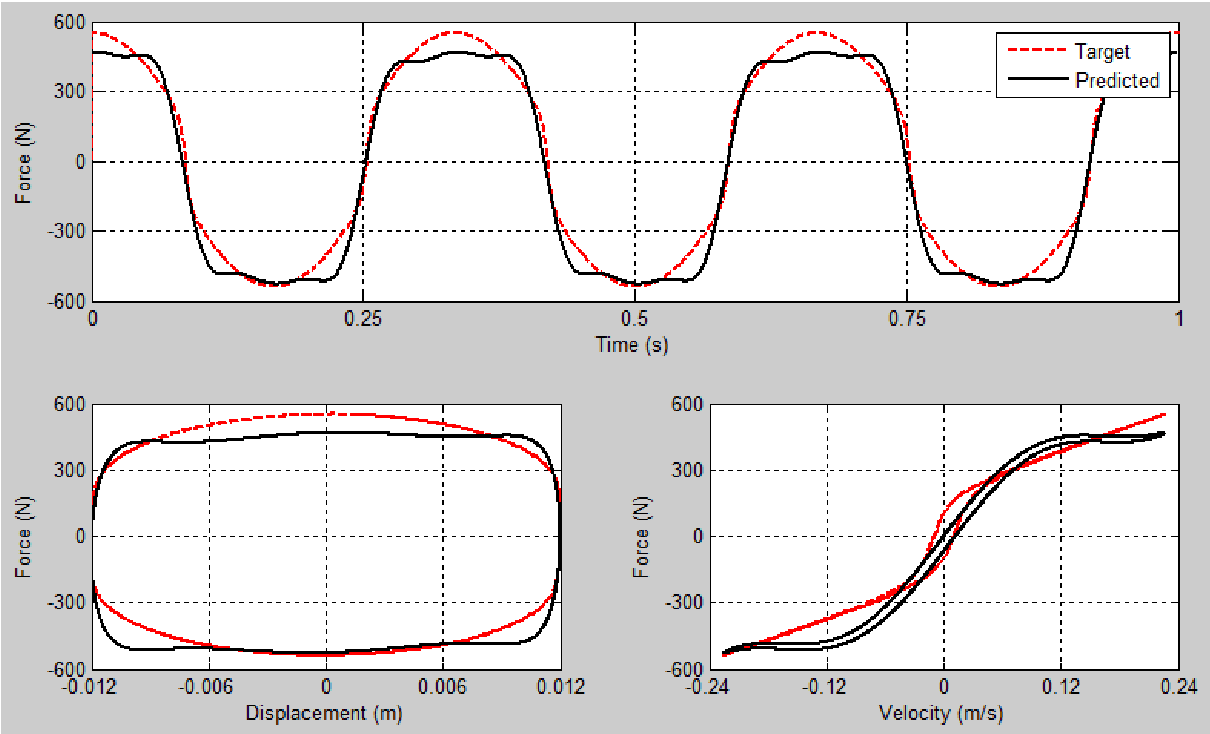

Figure 4: Validation of interpolation procedure derived from surface plot in figure (1) according to the validation set 2.

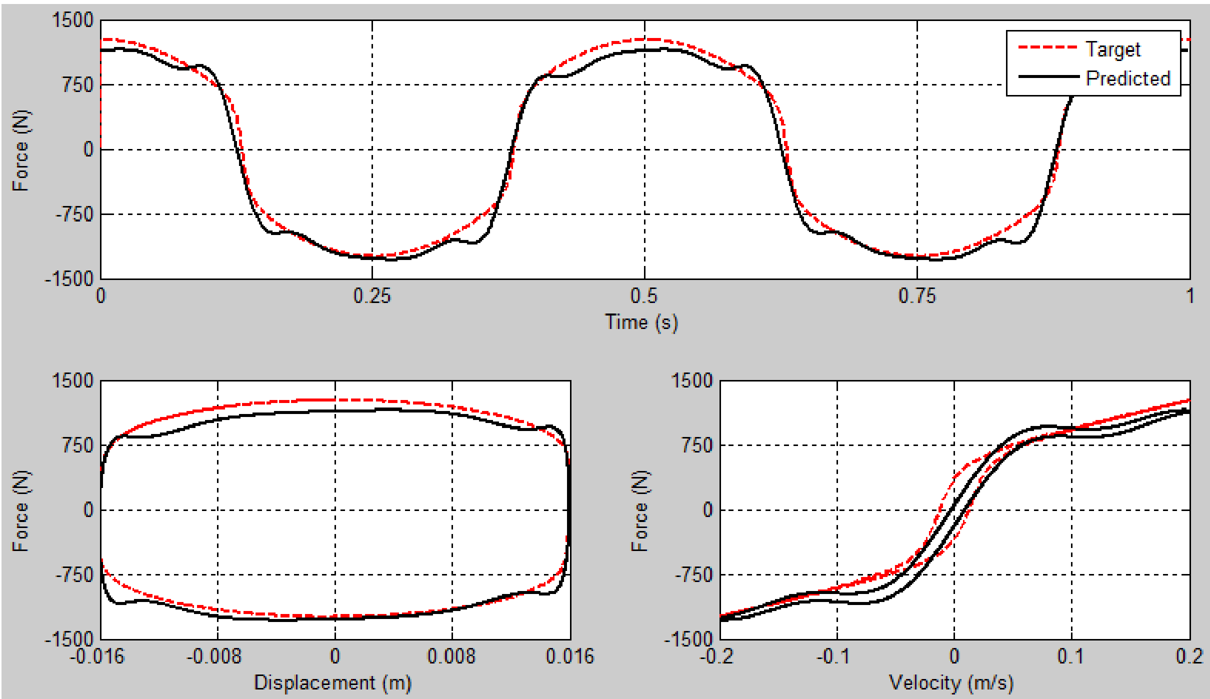

Figure 5: Validation of interpolation procedure derived from surface plot in figure (2) according to the validation set 1.

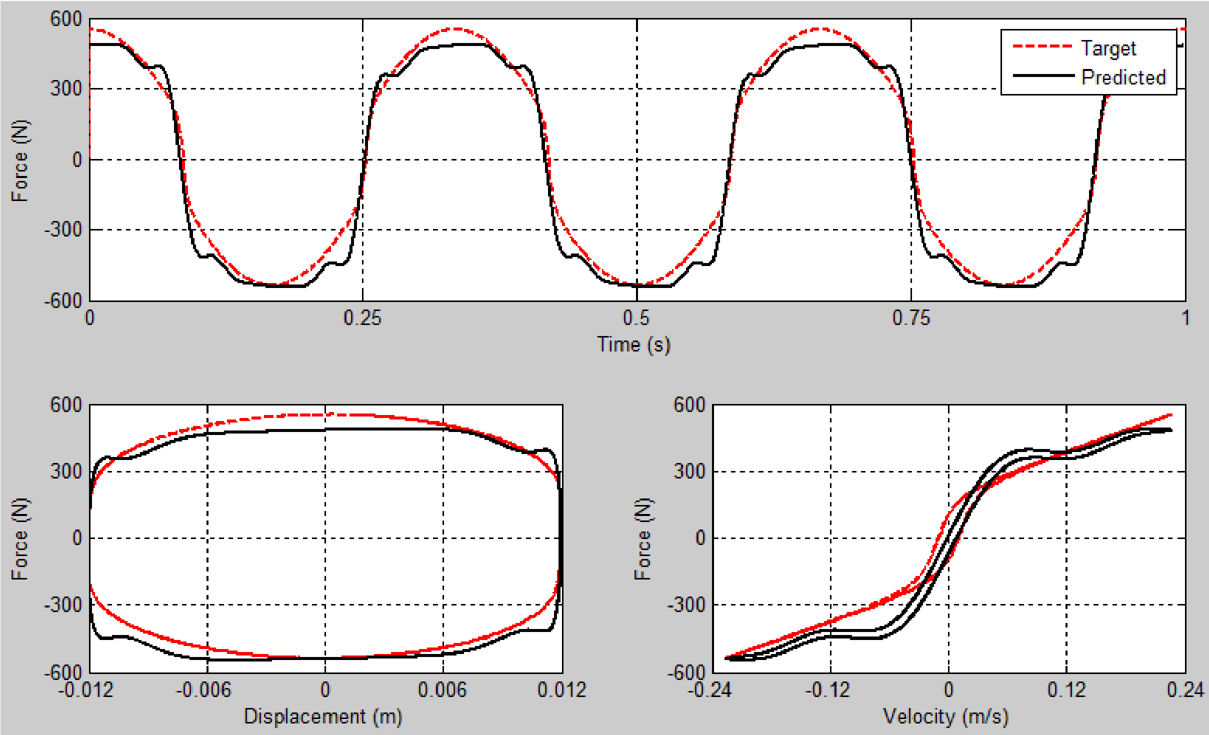

Figure 6: Validation of interpolation procedure derived from surface plot in figure (2) according to the validation set 2.

4.2 Identification from velocity-acceleration surface

A two-dimensional interpolation of the damper force as a function of velocity and acceleration for a fixed voltage of 1.5V is done. Following the two different ways in Section 4.1 to generate the above described constant voltage surfaces:

(i) by "weaving" the surface from the results obtained from a series of tests conducted with prescribed sinusoidal displacement signals, all at the same frequency but of different amplitudes, according to the following input $A \sin (2f\pi t)$, A = [0.2:0.2:20] (mm) and f = 2 Hz. Figure (7) shows the generated surface plot produced by the target MR damper model according to this way, the forces at the grid points being indicated by red circles. These are used to calculate the 20×20 coefficients.

(ii) by "weaving" the surface from the results obtained from a series of tests conducted with prescribed sinusoidal displacement signals, all at the same amplitude but at different frequencies, , according to the following input $A \sin (2f\pi t)$, f = [0.02:0.02:2] (Hz) and A = 20 mm. This way produced an excellent surface as shown in figure (8), the forces at the grid points being indicated by red circles. These are used to calculate the 20×20 coefficients.

Figures (9-10) demonstrate a very good agreement between the predicted and target damper forces according to different validation sets, thus indicating that the proposed technique is able to predict the hysteresis force of the MR fluid damper accurately. Moreover, Figures (11-12) introduce a superior agreement between the predicted and target damper forces according to different validation sets, thus indicating that the RFS weaving in velocity-acceleration model at different frequencies is able to predict the hysteresis force of the MR fluid damper very accurately, effectively and offers a superior force tracking.

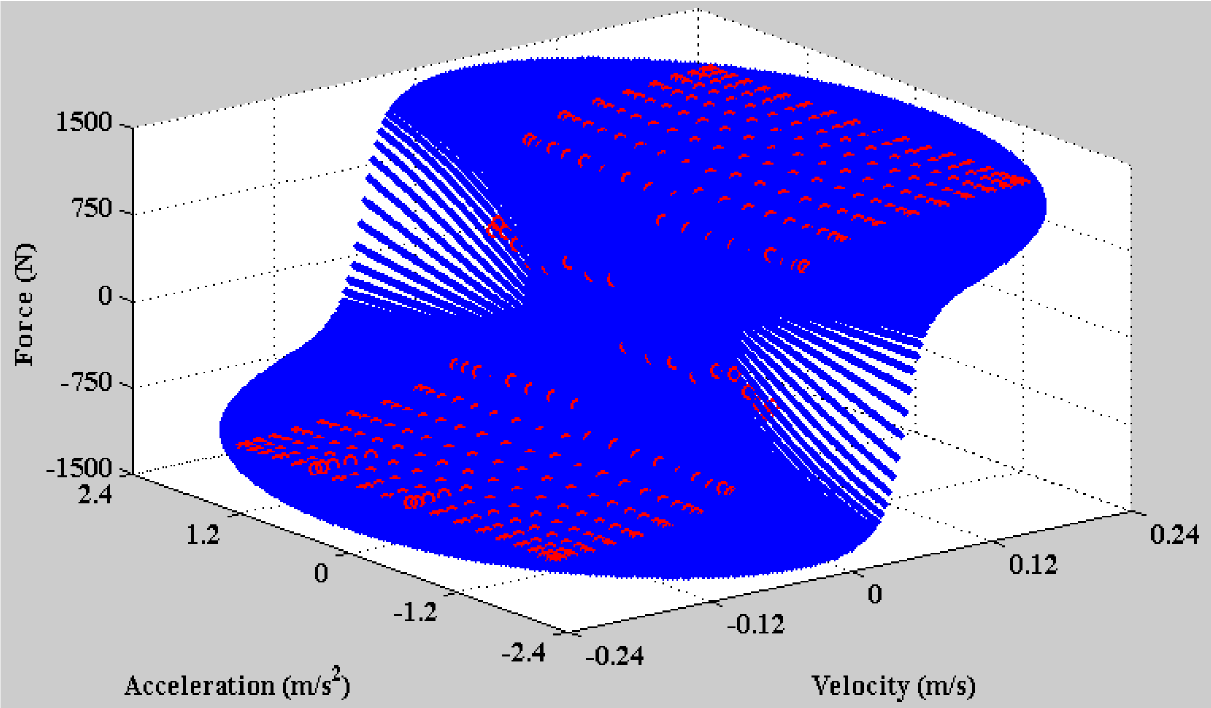

Figure 7: Surface plot of damping force generated by the target model according to different amplitudes.

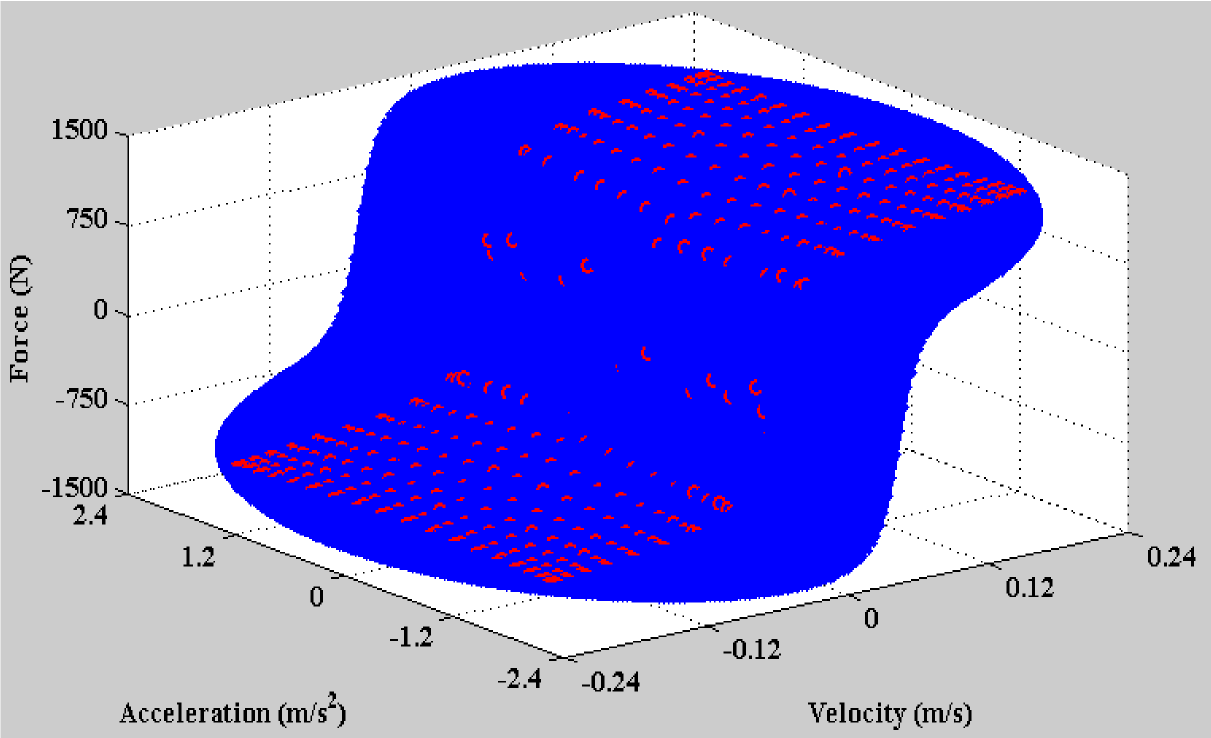

Figure 8: Surface plot of damping force generated by the target model according to different frequencies.

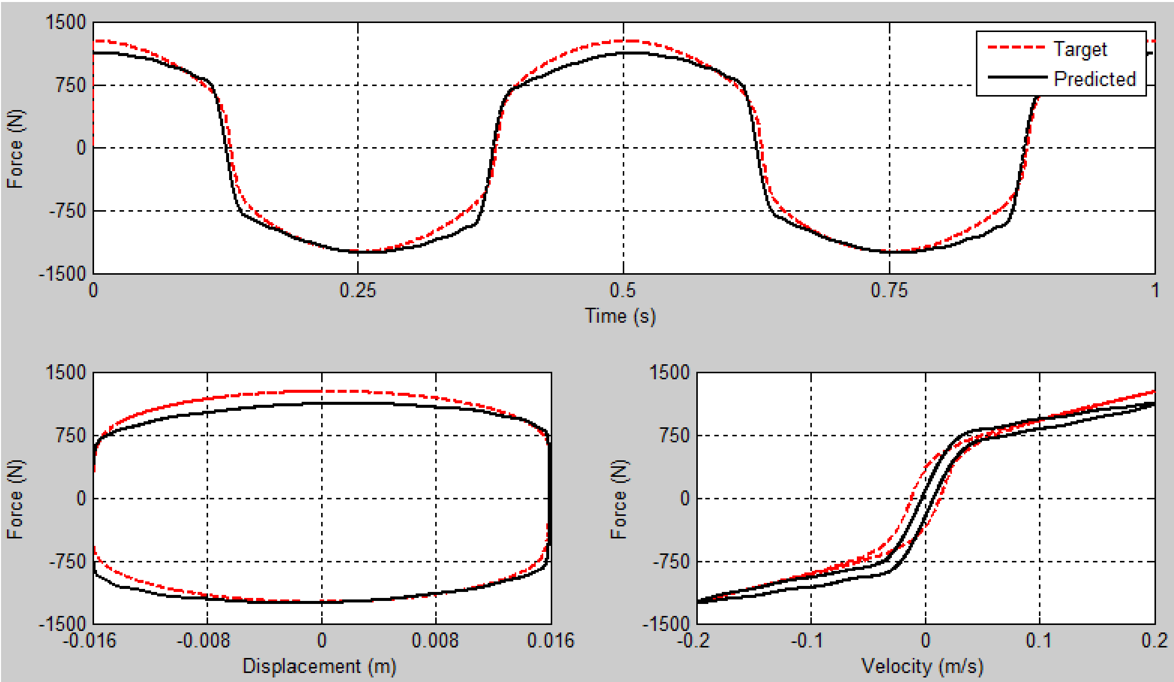

Figure 9: Validation of interpolation procedure derived from surface plot in figure (7) according to the validation set 1.

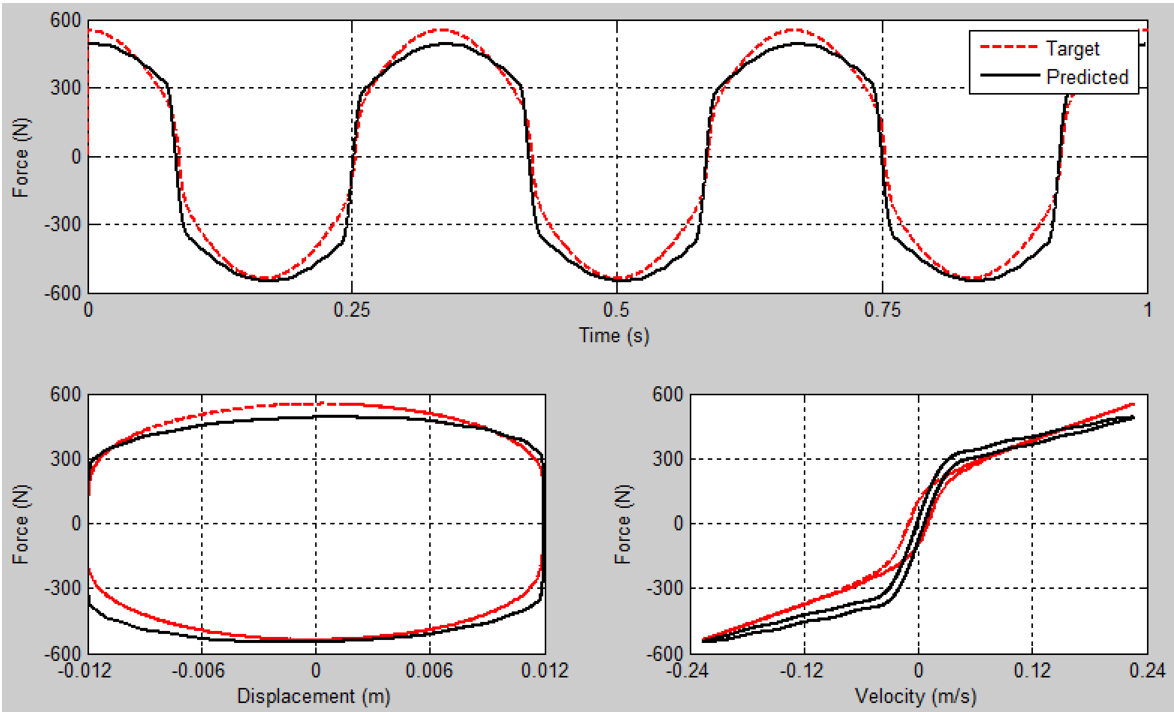

Figure 10: Validation of interpolation procedure derived from surface plot in figure (7) according to the validation set 2.

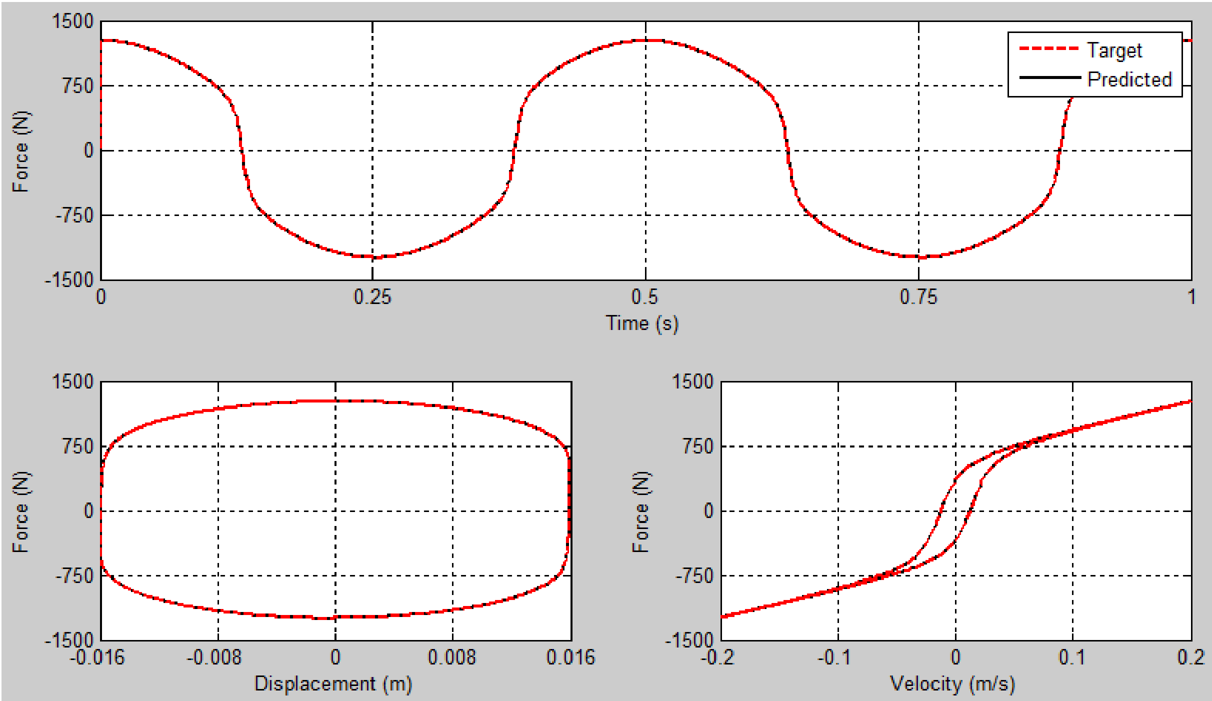

Figure 11: Validation of interpolation procedure derived from surface plot in figure (8) according to the validation set 1.

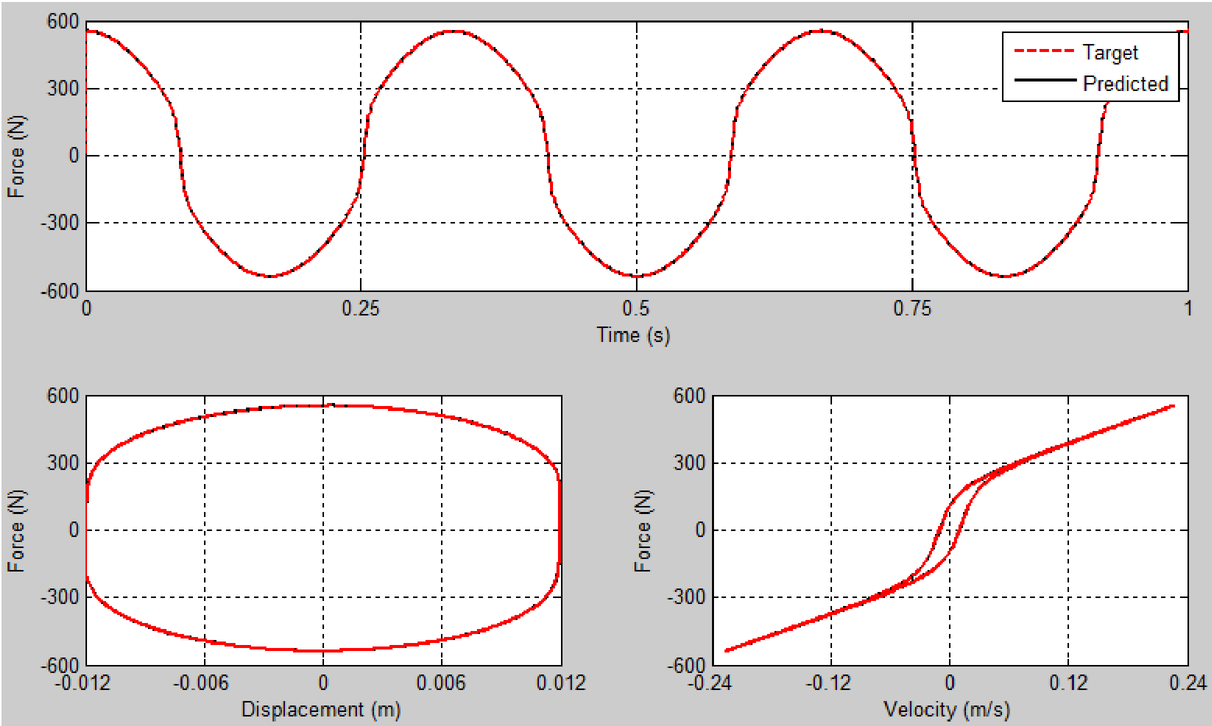

Figure 12: Validation of interpolation procedure derived from surface plot in figure (8) according to the validation set 2.

5 MODEL ACCURACY BASED ON RMS VALUES OF DAMPER FORCE

Equations (5-7) were introduced in [14] to quantify the effectiveness of predicted models against the target models. The RMS residual force (RMS_{RF}) evaluates how well the predicted modeling functions fit with the target model:

$$RMS_{RF} = \sqrt{\frac{\sum_{n=1}^{N}(F_p - F_t)^2}{N}} \tag{5}$$

where n is the number of data point, F_p is the predicted damper force (N), F_t is the target damper force (N) and N is the length of force vector. This can then be compared with the RMS force (RMS_F) of the target model to give the relative RMS force error ($\mathrm{R\_RMS_{FE}}$):

$$RMS_F = \sqrt{\frac{\sum_{n=1}^{N}(F_t)^2}{N}} \tag{6}$$

$$\mathrm{R\_RMS_{FE}} = \frac{RMS_{RF}}{RMS_F} * 100\ \% \tag{7}$$

Table (3) introduces the RMS_{RF} **,** RMS_F and $\mathrm{R\_RMS_{FE}}$ for the two validation sets based on the four restoring force surfaces. Also, a complete comparison between all predicted forces related to the target model based on different surfaces is proposed. The RMS_{RF} and $\mathrm{R\_RMS_{FE}}$ values indicate reasonable agreement between the target and predicted damper force. The proposed surface technique gives the lowest values of RMS_{RF} and $\mathrm{R\_RMS_{FE}}$ which confirms the success of constructing the restoring force surface in velocity-acceleration model. Moreover, the surface number (4) gives a superior prediction of the target damper force due to the excellence of restoring force surface and it's the most economical and efficient technique to formulate the RFS.

Table 3: Prediction accuracy based on RMS values compared with the target model

Id. case	RMS_{RF} **(N)**		RMS_F **(N)**		$\mathrm{R\_RMS_{FE}}$ **%**	
	Val. case 1	**Val. case 2**	**Val. case 1**	**Val. case 2**	**Val. case 1**	**Val. case 2**
Surface 1 Figure (1)	134.8	130.1	1059.4	670.2	12.7	19.4
Surface 2 Figure (2)	172.2	158.7	1059.4	670.2	16.3	23.7
Surface 3 Figure (7)	88.3	87.8	1059.4	670.2	8.3	13.1
Surface 4 Figure (8)	22.5	19.1	1059.4	670.2	2.1	2.8

6 CONCLUSIONS

In this article, a particular selection of data input to the RFS to predict the damping force of MR dampers, for the first time, has been proposed. An RFS method for estimating the MR damper force based on acceleration feedback is presented due to the advantages of the accelerometers. It consists of a two dimensional interpolation using Chebyshev orthogonal polynomial functions to identify the damping force as a function of the velocity and acceleration. The model identification and its validation are done based on simulated data generated by a theoretical simulation of an MR damper. Validation data sets representing a wide range of operating conditions of the MR damper show that the usage of RFS to predict the damping force for known velocity and acceleration is reasonably more accurate and offers a superior tracking of the target force than the predicted based on displacement and velocity due to the excellence of restoring force surface.

ACKNOWLEDGMENTS

This publication was supported by the European social fund within the frame work of realizing the project "Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague, CZ.1.07/2.3.00/30.0034. Period of the project’s realization is 1.12.2012 – 30.6.2015.

REFERENCES

[1] H. Metered, *Modelling and control of magnetorheological dampers for vehicle suspension systems*, Ph.D Thesis, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK , 2010

[2] W. Chooi, S. Oyadiji, Mathematical modelling, analysis and design of magnetorheological (MR) dampers. *ASME Journal of Vibration and Acoustics*, **131**, 061002-10 pages, 2009.

[3] W. Chooi, S. Oyadiji, Design, modelling and testing of magnetorheological (MR) dampers using analytical flow solutions. *Computers and Structures*, **86**, 473-482, 2008.

[4] N. Kwok, P. Ha, T. Nguyen, B. Samali, A novel hysteretic model for magnetorheological fluid dampers and parameter identification using particle swarm optimization. *Sensors and Actuators A: Physical,* **132**, 441-451, 2006.

[5] A. Elsawaf, H. Metered, T. Vampola, Z. Šika, Parameter identification of magnetorheological damper using particle swarm optimization. *2nd International Conference on Advances in Civil, Structural and Mechanical Engineering (CSM 2014).* 16-17 Nov., 2014, Birmingham, UK.

[6] B. Spencer, S. Dyke, M. Sain, D. Carlson, Phenomenological model for magnetorheological dampers. *Journal of Engineering Mechanics*, **123**, 230-238, 1997.

[7] N. Kwok, P. Ha, T. Nguyen, B. Samali, Bouc–Wen model parameter identification for a MR fluid damper using computationally efficient GA. *ISA Transaction*, **46**, 167-179, 2007.

[8] H. Metered, P. Bonello, S. Oyadiji, Nonparametric identification modeling of magnetorheological damper using Chebyshev polynomials fits. *SAE International Journal of Passenger Cars - Mechanical Systems*, **2**, 1125-1135, 2009.

[9] H. Metered, P. Bonello, S. Oyadiji, The experimental identification of magnetorheological dampers and evaluation of their controllers. *Mechanical systems and signal processing*, **24**, 976-994, 2010.

[10] H. Metered, S. Mostafa, S. El-Demerdash, N. Hammad, M. El-Nashar, Testing, Modelling and Analysis of a Linear Magnetorheological Fluid Damper under Sinusoidal Conditions. *SAE 2013 World Congress & Exhibition*, 16 – 18 April, 2013, Detroit, Michigan, United States.

[11] A. Shehata, H. Metered, W. Oraby, Identification of Hysteretic Behavior of Magnetorheological Dampers using NLARX Model. *Smart Structures and Systems, VETOMAC X Conference, Vibration Engineering and Technology of Machinery. Springer International Publishing*, 2015. pp. 733-742, 9-11 Sept 2014, Manchester, UK.

[12] F.Rodrigues, F. Thouverez, C. Gibert, L. Jezequel, Chebyshev Polynomials Fits for Efficient Analysis of Finite Length Squeeze Film Damped Rotors. *Engineering for Gas Turbines and Power*, **125**, 175-183, 2003.

[13] Mason, J. C. and Handscomb, D. C., Chebyshev Polynomials (Boca Ration, FL: CRC Press), 2003.

[14] V.Yung, D. Cole, Modelling high frequency force behaviour of hydraulic automotive dampers. *Vehicle System Dynamics*, **44**, 1-31, 2006.